CHAPTER 9

System Shutdown and Confirmation of Cleanup

9.1. Introduction. Robust remediation systems like ISTR are expensive to operate for extended periods. Therefore, to ensure efficient remediation operations, it is important to monitor for and understand the data that are gathered in the context of achieving the remediation goals. Decisions about the continued operation and eventual shutdown of an ISTR system typically hinge on whether or not the system has reached a point of diminishing returns with respect to the anticipated performance.

9.1.1. While performing ISTR, the project manager or engineer is typically monitoring a number of parameters: subsurface temperature (distribution and trends), concentrations of organic compounds in the recovered vapor, vapor flow rates, groundwater flow rates, condensate recovery, steam injection rates, electricity (or fuel) consumption, groundwater concentrations, and, potentially, periodic soil sampling results. These parameters are used to monitor the system operations, track treatment progress, and determine when the system should be shutdown.

9.1.2. Operation of an ISTR system should cease when remediation objectives, as specified for the treatment area, have been met. As described in Paragraph 4-2, remediation objectives for ISTR can be based on numerical targets (e.g., soil cleanup levels) or other measurable end-points or narrative goals established prior to treatment (e.g., mass removal percentage). This paragraph discusses various strategies and protocols used by the industry, many of which have been accepted by regulators, to confirm and document cleanup using ISTR. Multiple indicators of ISTR performance (lines of evidence) are used to determine when to terminate the thermal treatment phase and transition to a more passive polishing stage or to site closeout.

9.2. Shutdown Strategy. Before starting an ISTR system, it is important to not only establish technology-specific objectives for the response action (e.g., numerical cleanup levels or narrative goals), but to have in hand an overall exit strategy for the site that will guide the project manager or engineer through subsequent phases of the remediation, including transition and termination. According to recent DOE guidance on groundwater response strategies (U.S. Department of Energy 2002), an exit strategy consists of four essential elements**:**

a. A description of the objective of the activity, i.e., the objective associated with a technology application or phase of a response.

b. A performance “model” that describes the expected course of the remediation process, i.e., how conditions are expected to change over time from the current state until the response objective is attained.

c. A set of the performance metrics, decision criteria, and endpoints that will be used to assess how the response is progressing, demonstrate when the objective has been reached or an unacceptable condition or deviation occurs.

d. A contingency plan that will be implemented if data indicate an objective will not be met.

9.2.1. With a clear understanding of the expected performance and endpoints established, decisions about shutdown can be made. It can be difficult, however, to predict the performance of ISTR systems and come up with reproducible end-points and shutdown criteria because there are limited performance data from full-scale ISTR deployments. Therefore, expert field judgment must be relied upon to determine when to shut a system down and a certain amount of flexibility must be incorporated into the exit strategy.

9.2.2. Shutdown of an ISTR system requires ongoing assimilation of data from the various lines of evidence, which include subsurface temperature profiles and contaminant removal or destruction rates, to decide whether remediation objectives have been met. When an assessment of these lines of evidence tells the project manager or engineer that performance objectives are not being met, efforts to optimize or enhance the ISTR system in some way should be made. If the assessment indicates that the system will not likely succeed within the constraints of the existing design, then it may be necessary to implement a contingency plan.

9.2.3. Routine system monitoring data are collected and used by operators to assess system performance and make operational adjustments during operation. Details on monitoring for ISTR were discussed in Paragraph 8-1. System monitoring data, when viewed collectively, are used to evaluate and optimize system performance, as well as make critical judgments as to the effectiveness of treatment and help determine if continued operation is warranted.

9.3. Shutdown Criteria. Shutdown criteria are measurable, technology-specific parameters used by the project manager or engineer to gauge whether or not the current remedial phase is complete and the system is ready to be shutdown or transitioned to the next phase. Shutdown criteria for ISTR methods are typically based on numerical targets or endpoints against which process monitoring data are compared. Establishing shutdown criteria, like RAOs, requires an understanding of the potential performance capabilities of the selected ISTR technology and the expected or theoretical behavior, as well as the overall remediation goals. But it also must take into consideration the practical limitations of verifying the performance of ISTR in the field. System performance and optimization may focus on optimizing mass removal from the subsurface, yet remediation goals are typically (soil or groundwater) concentration based.

a. It is difficult to directly monitor subsurface conditions and the real-time effects of thermal treatment on the source zone. Piping, cables, and wiring for monitoring systems make access to interior treatment areas difficult. Further, drilling into and handling of hot soils and groundwater present health and safety concerns. If shutdown criteria are unreasonable or impossible to quantify using readily available instruments, then the decision to cease operation of the system is typically made on the basis of temperature data and trends in mass removal. In certain instances, shut down decisions may be made based on non-technical criteria, such as operating costs or remedial timeframe, which may appear as arbitrary endpoints.

b. Unlike RAOs, which are broader and tend to focus on reducing source area volumes (or mass) or contaminant mass flux to groundwater to attain a certain level of risk reduction or protectiveness, shutdown criteria are inherently process or technology-specific. Shutdown criteria should be based on parameters that are easy and inexpensive to measure, most of which are already collected as part of the system's process monitoring program (e.g., temperature profiles, vapor concentration). Direct measures of contaminant mass remaining in the subsurface, based on collection of soil samples, for instance, have not been typically used as shutdown criteria owing to the difficulty in sampling hot media and the need to make quick, cost-effective decisions regarding continued operation of a remedial system. The following section discusses some of the parameters that can be considered for use as shutdown criteria at ISTR projects.

9.3.1. *Mass Removal*. A goal of source zone remediation may be to reduce the mass of NAPL in the subsurface. By charting the amount of NAPL recovered from the subsurface over time, the technology's performance can be assessed and used as a basis for system shutdown. The mass of NAPL brought to the surface by the extraction system can be estimated by measuring the concentrations of contaminants in the extracted fluids (liquids and vapors) before these streams enter aboveground treatment units. NAPL content and the concentrations of site contaminants in extracted water and vapor are typically measured as part of the process monitoring scheme and can be used as shutdown criteria, forming two or three lines of evidence.

9.3.1.1. There are two ways in which mass removal information can be utilized as a shutdown criterion: mass removal percentage and mass removal rate. Of the two, determining the percentage of mass removed is the more difficult and uncertain calculation to make because of the difficulties inherent in quantifying or measuring contaminant mass either before or after treatment.

9.3.1.2. If a fairly accurate estimate of the mass is available before the start of ISTR, then it may be useful to track the cumulative mass recovered in the extracted fluids and shut down the system after a certain percentage of the mass believed to be present initially is recovered. The level of confidence of initial estimates of NAPL mass is often low, and based on inaccuracies inherent with sampling. Some initial estimate is usually made to define the potential mass to be removed for permitting purposes and estimates of loading on surface treatment systems. There have been cases where greater than 200% of the mass originally present in the treatment area was removed, which does not reflect well on the accuracy of the pre-treatment characterization or the use of mass removal percentage as a criterion for shutdown.

9.3.1.3. A better strategy is to operate the ISTR system until the rate of mass removal, based on observations of vapor or aqueous-phase concentrations in the extracted fluids, reaches a point of diminishing returns or until no NAPL product is recovered. Similar to SVE systems, vapor concentrations often approach an asymptote at some level where increases in the rate of energy input (in the form of heat for ISTR) fails to result in a higher mass removal rate. Asymptotic conditions alone may not be reason to shut down an ISTR system, particularly if there is still significant mass being removed from the ground. A criterion suggested for SVE system shutdown is "specific energy consumption," defined as the amount of energy needed to remove 1 kg of chlorinated hydrocarbons from the unsaturated subsoil using SVE. However, in taking this approach, a well designed and constructed vapor recovery system is required that one is confident is being effective. To evaluate that treatment is complete, the rate of removal should be the result of limited vapor recovery rather than the result of leaks diluting the concentrations.

9.3.2. *Temperature Distribution*. A measure of performance often used as the initial basis for shutdown of ISTR systems is temperature distribution and duration. Temperature monitoring is integral to any ISTR project, providing a measure of heat distribution and a way to evaluate the effectiveness of energy delivery to the treatment zone (methods of temperature monitoring are discussed in Paragraph 8-1.3). Temperature distribution is typically used as a shutdown criterion in conjunction with other lines of evidence, such as concentrations of VOCs in the vapor recovery system. If the desired temperature is attained throughout the treatment area, and concentrations in the vapor recovery system are declining or trending towards an asymptote, then the system is at or near the end of its useful period of operation. Depending on the particular ISTR technology and the contaminants to be treated, a target temperature and residence time required to mobilize or destroy the contaminants would have been established during the design. Attaining and maintaining this temperature throughout the treatment zone for a specified period would therefore likely be a performance objective for the ISTR system and a decision criteria operation.

9.3.3. *Groundwater Concentration.* Restoring groundwater quality in the vicinity of a NAPL source area being treated by ISTR is one of the most commonly stated remediation objectives. This is because of the presence of residual NAPL in the saturated zone and the slow release and dissolution of these contaminants from the NAPL phase into the groundwater phase. During ISTR treatment, it is common for concentrations in groundwater to increase in response to heating. This is attributable to the temperature-sensitive nature of aqueous solubility and also to disturbance of the subsurface during treatment. The concentrations in groundwater increase until the boiling point of the mixture of VOCs in groundwater is achieved, and then concentrations in groundwater decline. It is also important to monitor groundwater quality outside the source area during ISTR to ensure that containment is being achieved. It is not recommended that groundwater chemistry data alone be used to determine when to shut down an ISTR system.

9.3.4. *Plume Load*. Another indicator of performance based on measurements of groundwater quality is to track decreases in plume load or the mass release rate at steady state from the NAPL source to the groundwater plume. Plume load is the “rate at which solute mass in the groundwater plume crosses a spatial plane oriented at a right angle to the direction of groundwater flow.”* Using plume load as a criterion, shutdown of the ISTR system would be considered when the mass release rate from the source to the groundwater falls below the natural assimilative capacity of the aquifer. This obviously requires an understanding of the natural assimilative capacity of the aquifer (see Paragraph 4-2). Perhaps the simplest and most direct way of calculating plume load entails capturing the entire plume using one or more extraction wells pumping at a continuous rate and collecting steady-state concentration data. Based on the measured flow rate and concentration data, plume load can be calculated. This could be a cost-effective approach to system shutdown, especially for ISTR systems that completely control the plume using hydraulic containment. Another way to measure plume load is to collect groundwater data from numerous, closely spaced sampling points along a transect of wells oriented perpendicular to the direction of groundwater flow using direct-push, multi-level

* North Atlantic Treaty Organization/Committee on the Challenges of Modern Society. NATO/CCMS Pilot Study, Evaluation of Demonstrated and Emerging Technologies for the Treatment of Contaminated Land and Groundwater (Phase III). EPA 542-R-02-002.

sampling tools. The plume load is then calculated by multiplying the estimated groundwater flow velocity by the average groundwater contaminant concentration. This method requires relatively more sampling costs but allows for more rapid decision-making and analysis.

9.3.5. *Emerging Methods to Track Remediation Progress*. Isotopic techniques provide a possible method to track progress of ISTR remediation and may be factored into decision making to shut down the systems. Stable isotopes of carbon and chlorine have been used to track the progress of an ISTR groundwater remediation site in the greater Chicago Area (Sturchio et al. 2000). Researchers there determined that isotopes of ^{13}C and ^{37}Cl in groundwater contaminated with chlorinated compounds show increases in both ^{13}C and ^{37}Cl when the chlorinated compounds were being biodegraded. Where volatilization of chlorinated compounds from groundwater systems was occurring, the groundwater was enriched in ^{37}Cl, but ^{13}C concentrations decreased. Heat enhanced dissolution into groundwater was reflected in a reduction of both ^{13}C and ^{37}C. This relationship is presented in Figure 9-1. Plotting concentrations of $\delta^{13}C$ and $\delta^{37}Cl$ over time provides insight into the fate of the compounds, and hence the active fate mechanism.* For instance, Figure 9-2 presents data from well F3 from the site over various sampling events. The single data point located on the left portion of the graph is a reference standard for the site from a sample of DNAPL in water recovered earlier in the ISTR remediation process. Samples from January 1998 and April 1998 showed a trend toward this reference standard, and this was interpreted as heat-enhanced dissolution into groundwater, consistent with the pattern depicted in Figure 9-1 (Sturchio et al. 2000). From April to December 1998, the trend was relatively flat, such that there may have been a combination of biodegradation and volatilization. The data trend from December 1998 to January 1999 indicated that volatilization was occurring. Treatment was discontinued after January 1999, for this well had achieved the cleanup criteria. Well Ca6 (Figure 9-3) from the same Chicago area site is particularly interesting, for there was concern that DNAPL had continued to persist at this location during treatment. There was concern that the presence of DNAPL would be toxic to microorganisms and biodegradation would not contribute to concentration reductions. However, the isotopic data from this well show a consistent trend, indicating that biodegradation is the predominant fate mechanism, and the well later achieved the cleanup criteria after termination of active thermal treatment.

9.3.5.1. The utility of this technique is that it provides a greater understanding of the mechanisms in the subsurface, which in turn leads to better understand of the groundwater monitoring data, from which to make informed decisions on remedial progress and when systems may be shut down can be made. These isotopic data assisted the project manager in making decisions as to whether portions of the treatment system could be shut down, what areas required additional treatment, and which areas were being treated according to plan.

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* Isotopic data are expressed in conventional δ notation, where $\delta = [(R_{sample}/R_{reference}) - 1] \times 1000$, R= $^{13}C/^{12}C$ or $^{37}Cl/^{35}Cl$, and δ values are reported in units of $^{o}/_{oo}$ (per mil)

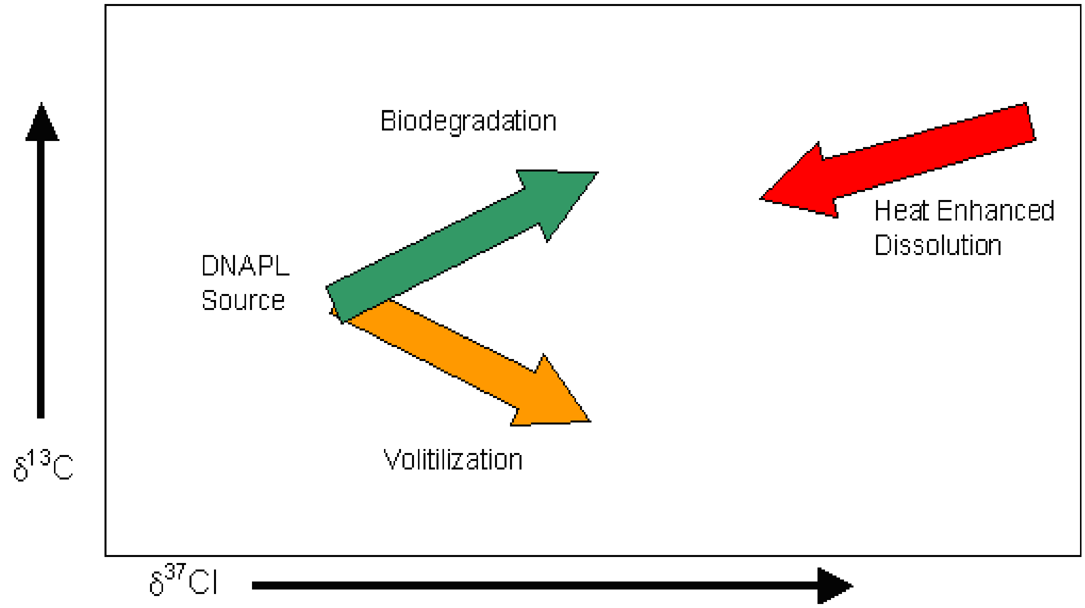

Figure 9-1. Changes in Isotopic Composition of Groundwater Contaminated with Chlorinated Organic Compounds Under Three Scenarios.

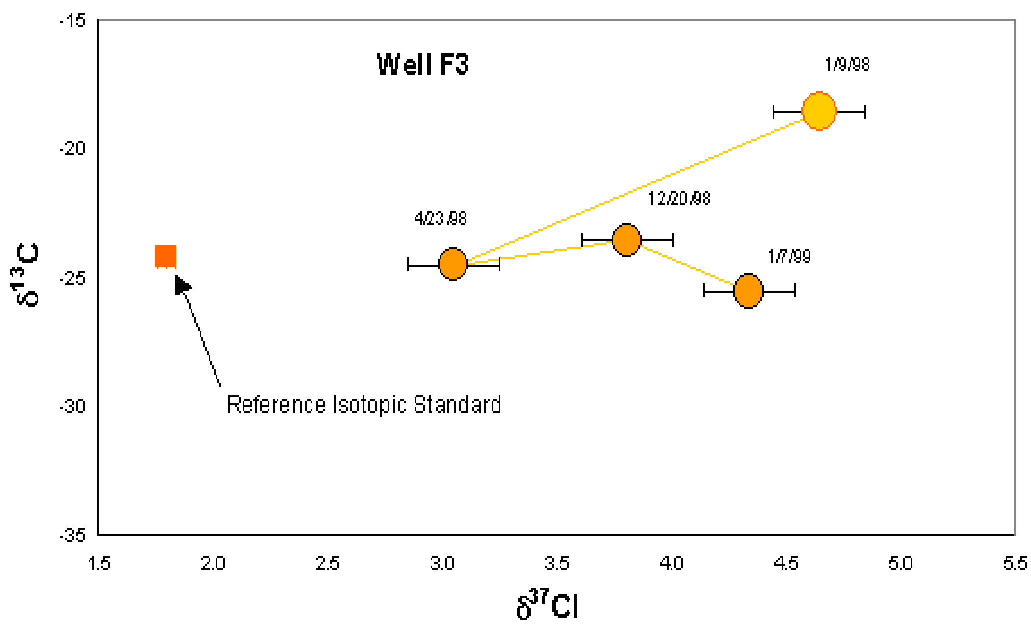

Figure 9-2. Well F3, Changes in Groundwater Isotopic Constituents During Thermal Treatment.

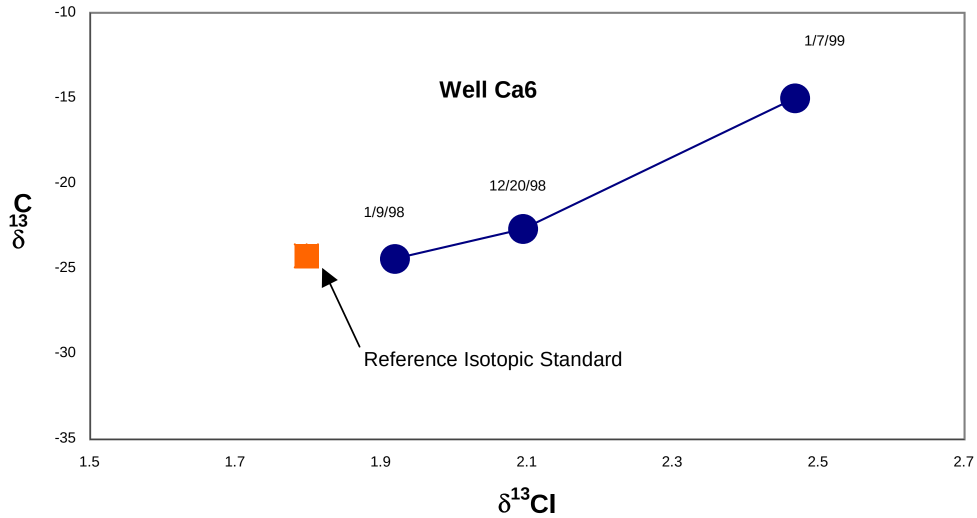

Figure 9-3. Well Ca6, Changes in Isotopic Constituents in Groundwater During Thermal Treatment

9.4. Confirmation of Cleanup. Once shutdown criteria have been reached and a decision to turn off the system has been made, based on multiple lines of evidence, it is important to compare the results to remediation objectives and confirm that the cleanup requirements have been met. This usually entails collection and analysis of environmental media within the treatment area and a statistical evaluation of the resulting chemical concentration data.

9.4.1. *Sampling Strategy*. Before collecting samples of soil or groundwater, it is important to devise a plan for generating and analyzing the confirmatory data, the goal of which is to verify that cleanup has taken place. Details of the post-treatment sampling should be presented in the *Sampling and Analysis Plan*. In general, the confirmatory sampling program should be more exhaustive, both spatially and analytically, than that used during routine monitoring. The confirmatory sampling plan should be designed and implemented in accordance with statistically derived protocols and procedures, taking into account the estimated variability of concentrations and the desired level of confidence. Biased sampling may be appropriate in areas that were furthest from the heat sources or in areas that did not fully reach target temperatures or reached target temperatures for the least amount of time. This would be particularly applicable in cases where the remedial objectives required achieving a baseline contaminant concentration or NAPL content throughout the treatment volume. Rigorous adherence to quality assurance/quality control procedures is also critical at this stage.

9.4.1.1. The sample collection approach specified in the plan will also depend on the media-specific remediation objectives. If the RAO was to meet numeric cleanup criteria for soil, then a soil sampling program must be designed and implemented to demonstrate cleanup. If the RAO was to reduce the plume load, then measurements of groundwater concentrations at points along a transect or some other method of measuring mass release rate must be incorporated into the sampling design.

9.4.1.2. When verifying groundwater cleanup, sampling should be spaced temporally over at least two sampling rounds to check for rebound effects following cessation of heating. For example, at the Pinellas STAR Center in Largo, FL, the work plan called for sampling groundwater from select wells every 2 weeks during the operational phase. After shutdown, three more rounds of sampling were to be conducted after remediation was completed (at 4 weeks, 12 weeks, and 24 weeks).

9.4.2. *Sampling Hot Media*. One of the problems encountered when attempting to confirm cleanup at ISTR projects is collecting samples of groundwater or soil that have not yet cooled to ambient temperatures. Characterizing soil and groundwater contaminated with volatile organic compounds (VOCs) is challenging because of the difficulties associated with minimizing VOC loss at ambient temperatures. At elevated temperatures, this problem is exacerbated as heat enhances volatilization and the potential for VOC loss increases. Sampling hot media also presents a safety hazard and extreme care should be taken to avoid burns from the unexpected formation and release of steam (steam flashing). The ISTR treatment needs to be shut down in advance of sampling to allow pressures in the subsurface to dissipate. Temperature monitoring as part of the remediation system operations will indicate when sampling may be done. Extreme caution should still be exercised, especially when sampling wells screened below the water table. At an ERH project in Portland, OR, a sampling technician was seriously burned when he tried to collect a groundwater sample with a bailer and steam flashed out of the well onto his neck and face.

9.4.2.1. The process of collecting and handling samples of hot media can be avoided by delaying the sampling effort until the subsurface cools to near ambient temperatures. However, this may not be possible, as it may require waiting up to 12 months for the subsurface to cool before verifying cleanup. At the DUS/HPO demonstration project conducted at the Savannah River Site in Aiken, SC, steam injection ceased in September 2001, however, more than 11 months of cooling were required before confirmation sampling could be done using conventional methods.

9.4.3. *Collecting Soil Samples*. A simple method of minimizing VOC losses during soil sampling was developed and tested at Launch Complex 34, Cape Canaveral Air Station, FL, during confirmatory drill-back sampling at the ERH demonstration site (Gaberell et al. 2002). The method involved the collection of soil cores in metal or acetate sleeves and placement of the sleeves in an ice bath, after capping both ends, to cool the heated cores to ambient temperatures. The temperature of each core was monitored using a thermometer; once they reached ambient groundwater temperature (around 20°C), small aliquots of soil from each core sample were transferred to jars containing methanol (EPA Method 5030).

9.4.4. *Collecting Groundwater Samples*. Sampling groundwater while it is still hot can be dangerous, but can provide another way of monitoring progress. Care must be taken to avoid getting burned by flashing vapors emanating from monitoring wells. Groundwater samples should be obtained in a manner consistent with the discussion in Paragraphs 8-1.4.1 and 10-2, and not be collected from subsurface zones that are not vented to prevent steam from building up and being released when a well cap is removed. Technicians should wear protective clothing and goggles whenever working in areas undergoing ISTR. To avoid contact with hot liquids, and to minimize the loss of volatile contaminants from the water samples, samples should be collected using low flow sampling methods. Permanent, dedicated tubing, accessible without opening the well cap, should be installed in each well and run through an ice bath before collecting the sample.